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Summary

This report summarizes the design details and initial test results of a superconducting magnetic mirror facility that has been constructed at NASA Lewis Research Center for use in thermonuclear research. The magnet system consists of four solenoidal coils which are individually rated at 5.0 T. Each coil is composed of an inner, middle, and outer winding. The inner winding is wound of stabilized Nb_3Sn superconducting ribbon, and the middle and outer windings are wound of stabilized Nb-Ti superconducting wire. When arranged in the mirror geometry, the four coils will produce 8.7 T at the mirrors and a 1.8 mirror ratio. The magnet has a 41-cm diameter clear bore which is open to atmosphere. Distance between the mirrors is 111 cm. Presently there are only three magnets in the facility; the fourth magnet is being rebuilt.

Introduction

This report presents the design criteria, construction details, and initial test results of a versatile superconducting magnet facility for use in plasma physics research. The SUMMA*facility is unique in that it has the highest design field strengths for its bore size of any known superconducting magnet.

Thermonuclear research is conducted at NASA Lewis Research Center (LeRC) as part of its responsibility to evaluate advanced power and propulsion concepts for space applications. SUMMA is an outgrowth of the steady-state plasma heating research program conducted for over a decade at LeRC. Preliminary studies indicated that superconducting magnets and steady-state operation were desirable for space applications.[1,2,3] SUMMA was intended to advance the superconducting magnet technology, and to gain design and operating experience with other advanced technology subsystems that constitute a high field plasma research facility.

Originally, SUMMA was to be the next generation machine in the ion cyclotron resonance heating (ICRH) program at LeRC.[4] When emphasis shifted from stellarators to tokamaks, the need diminished for ICRH studies in straight magnetic field sections. Consequently, it was decided to install a "BURNOUT-type"[5,6,7] steady-state dc plasma heating experiment in SUMMA. According to scaling laws developed at ORNL for their BURNOUT experiment, plasmas with ion temperatures in excess of ten keV and densities of 10^{14} cm^{-3} are predicted for the field strengths in SUMMA. These scaling laws will be tested in SUMMA. Such a fusion-like plasma, in the large SUMMA volume, would be of utility for studying both plasma phenomena and engineering problems associated with thermonuclear reactors.

Major Characteristics of SUMMA

The SUMMA facility includes four magnets and three spacers permitting seven different magnetic field configurations. Each magnet has an inner, middle, and outer winding that can be individually powered for further flexibility in shaping the magnetic field. The magnet bore is open to atmosphere, and each spacer has horizontal and vertical access ports open to atmosphere. The experimental volume is therefore completely isolated from the magnet facility vacuum. Modification to the experiment can be made while the magnet remains cooled to liquid helium temperature. The major parameters of SUMMA for the simple mirror configuration are listed in Table I. A side view of the facility in this configuration is shown in figure 1.

*SUperconducting Magnetic Mirror Apparatus

Table I
Design Parameters for SUMMA in Simple Mirror Configuration

	cm
Bore diameter	41.3
Wide spacer width	19.7
Wide spacer access port diameter	13.6
Narrow spacer width	12.1
Narrow spacer access port diameter	7.6
Magnet module width	33.7

Magnets Powered	All four Magnets	Two inboard Magnets
Max field at mirrors, T	8.7	5.8
Field at central plane, T	4.9	3.8
Mirror ratio	1.8	1.5
Distance between mirrors, cm	111.1	77.5

Superconducting Magnets

Design and Construction Details

Four identical superconducting magnets were specified for SUMMA. The design parameters and construction details of these magnets are already in the literature [8,9] and only a brief description will be given here. A design summary is given in Table II. Each magnet is capable of producing a central field of 5.0 T when operated alone. When two magnets are operated as a closely spaced pair they produce a central field of 8.8 T. The maximum field strengths and stresses given in Table II are for the closely spaced pair. The maximum load transmitted by the coil mandrels is 844 tons which occurs in the four magnet configuration with a separation of 15.2 cm between coils.

The inner winding, exposed to a maximum field of 10.3 T, uses Nb_3Sn superconducting ribbon (strengthened with stainless steel and stabilized with copper) wound into 20 pancake sections. The middle and outer windings, exposed to lower field strengths, are layer wound with an Nb-Ti superconducting wire consisting of 15 strands of Nb-Ti embedded in a square cross section of OFHC copper substrate. The copper is both the load bearing material and the stabilizer.

For the tests reported herein, only three magnets were used. The fourth magnet is being rewound and will be installed later.

Table II Magnet Design Summary for 5.0 T Superconducting Magnets

	Inner Winding	Middle Winding	Outer Winding
Winding height, cm	30.48	30.48	30.48
Inside winding radius, cm	25.40	28.57	37.15
Outside winding radius, cm	28.26	36.83	45.40
Conductor	Nb_3Sn	Nb-Ti	Nb-Ti
Conductor dimensions, cm	.005x.012	.086 sq	.086 sq
Conductor length, m	2636	8306	10,424
Number of turns	1500	4000	4000
Current, A	300	300	427
Maximum field at windings, T	10.3	8.0	5.6
Maximum stress			
Tensile* N/cm^2	23,979	19,788	25,765
Lateral, N/cm^2	2535	2082	3882
Self-inductance, H	1.1	5.7	13.8

*unsupported

Magnet Power Supplies and Control System

In testing the three-magnet configuration, each outer and each middle winding was individually pow-

ered by 0-500 amperes, 0 to 10 volt dc power supplies. Each of these supplies is programmable to provide both up and down ramping capability with presettable limits, a "hold" mode, and ramp rates from 1 to 990 seconds per ampere.

Figure 2 shows typical power supply connections and associated circuitry. Across the output of the supply is a diode shunt capable of discharging the coil with only convection cooling. With this diode in the circuit, only a small fraction of the discharge current is borne by the three-phase bridge rectifier diodes in the power supply which depend on blowers for their cooling. Thus in the event of a power failure to the supplies, no damage will result to the rectifiers. The discharge rate through the diode shunt is fixed by its voltage characteristic and the coil inductance, including mutuals. Presently the total discharge time for the three-coil system from full charge to zero is less than two hours. Provisions are made to add a diode in series as shown in figure 2 to shorten this discharge time to less than one hour.

In the event of an emergency shut down situation (i.e., coil normalcy, vacuum failure, helium loss, etc.) the coils can be discharged in approximately 1 minute by opening the contactor shown and allowing the coils to dump their energy into resistive shunts. These shunts are designed to limit the voltage across the coils to a safe value, and to precipitate a uniform normalcy throughout the windings. During a normalcy, about one-third of the stored magnetic energy is dissipated in the resistive shunts. The remaining energy appears as ohmic heat in the coil windings. These stainless steel resistive shunts are water cooled and have been used successfully to discharge the three magnets from their design current levels. Currents obtained from the instrumentation shunts (figure 2) are recorded on strip charts to assist in diagnosing normalcies.

Mechanical and Cryogenic Design

The SUMMA assembly consists of four magnet modules, three spacer modules, and two end modules (figure 1). This modular concept satisfied the requirements for variation in magnet positioning and spacing, and flexibility in electrical control, which required eight high current leads to each magnet. However, the modular concept imposed severe cryogenic constraints on the design. Additional constraints imposed by requirements for maximum access in two mutually perpendicular planes, and for maximum clear diameter in the magnet bore necessitated compromises in dewar insulation and shielding.

Magnet and Spacer Suspension System

A magnet module is shown in figure 3. The magnet is contained within a sealed (welded) type 310 stainless steel vessel. This helium vessel is supported and restrained by eight adjustable filament wound fiberglass-epoxy support straps. These straps transfer the weight out to the room-temperature outer vacuum shell. The spacer modules (figure 4) are similarly supported but with only four straps, positioned at the axial center plane. The spacers are cooled by contact with the liquid helium vessels. The spacer floats in the axial direction and will accommodate axial misalignment of the magnet or spacer up to the limit imposed by its touching the liquid nitrogen cooled radiation shield surrounding the access ports. The end modules complete the cryogenic closure of the dewar and also provide the axial restraint of the assembly.

Twelve tie rods pass through the assembly to the tie plates in the end modules. Pretensioning of these rods permits loads caused by internal pressure within the magnet helium vessel to be transmitted to the heavy tie plates.

From the end plates, the axial loads, including possible magnetically induced loads, are carried out to the dewar shell through three relatively heavy axial fiberglass-epoxy support straps at each end module.

Thus, wherever restraining loads are brought out from the 4.2° K helium vessels or spacers to the 300° K outer vacuum shell, fiberglass-epoxy tension straps are used. These straps are thermally shorted to the nitrogen cooled radiation shield at the point of penetration through the shield. These straps were found to have the highest figure of merit defined as the ratio of allowable design stress to thermal conductivity (2411 N-hr-°C/Cal-m). An intensive mechanical testing program was carried out on these straps. This included a 1000-cycle thermal shock test, followed by a 1000-cycle tensile fatigue test, and then an ultimate tensile test. No thermal conductivity measurements of the straps were made, but estimates were made from the known composition of the material.

Magnet Module

Shown in figure 3 is a magnet module. The magnet is contained within a sealed helium vessel and supported as discussed above. In addition to the support straps, the liquid helium temperature vessel has 12 connections to the room temperature outer vacuum shell. This includes eight electrical power leads, one liquid fill tube, one cold helium gas fill tube, one gaseous helium vent tube, and one tube containing instrumentation leads. The design of these tubes for minimum heat leak into the helium vessel will be discussed later.

The helium vessel contains a shroud around the magnet periphery. At the start of the cooldown process, cold helium gas is introduced at the bottom of the shroud. It then flows around baffles in the shroud and is vented at the top of the vessel. The baffles prohibit channeling and keep the gas velocity high for a good heat transfer coefficient. The shroud contains 12 relief valves, so that during a normalcy the large amount of gas liberated at the magnet can escape into the helium vessel.

During regular operation the liquid helium level slowly cycles between 11 cm and 19 cm from the top of the magnet. The total volume of liquid helium in the vessel is approximately 165 liters.

Magnet Lead Restraints. The magnet winding lead splices are immersed in the liquid helium. All magnet leads are contained and restrained by a system of fiberglass-epoxy (G-10) blocks, or tack-welded straps. Any motion of these leads could induce a magnet normalcy, so great care was taken to make a rigid installation.

Vapor-cooled Power Leads and Instrumentation Leads. In the vapor-cooled power lead tube, a sleeve of electrical insulation is located on the inside of the tube. At the top and bottom of the tube are copper rods electrically isolated from the tube by the sleeve. The magnet leads are soldered to the lower bar along its entire length. The top and bottom bars are electrically bridged together by copper wire mesh. Helium vapor from the vessel flows through the inside of the tube making intimate contact with the wire mesh for good heat transfer. The vapor picks up energy from the ohmic heating and is vented into the main helium vapor return line. The vapor flow rate through the tube is regulated by a thermostatically controlled valve which maintains the outlet vapor temperature near 300° K. The outside of the vapor-cooled lead tube is thermally shorted to the nitrogen-cooled radition shield at the point of penetration through the shield.

Helium Fill and Vent Tubes. The liquid helium fill tube, the gaseous helium fill tube, and the helium vapor vent tube are all cooled in a manner simi-

lar to the vapor-cooled leads. The vapor-cooled helium vent tube and relief valve assembly are shown in figure 5. Under steady-state operation, helium vapor spirals up the narrow annular passage between the inner and outer tubes, intercepting the heat coming from the room temperature outer vacuum shell. The vapor flow is regulated by a backpressure control valve. At the beginning of magnet cooldown, when cold helium gas is circulated through the vessel, the flow is sufficient to lift the inner weight off its seat, and much of the gas flows up the center tube and back to the recovery system. During a coil normalcy, when a still larger gas flow exists, the spring-loaded outer relief valve unseats and helium is vented to the atmosphere.

Spacer Module

A spacer module is shown in figure 4. There is no liquid helium vessel for the spacers, they are conduction-cooled by contact with the magnet helium vessels. In the simple mirror geometry, the three spacers are placed side by side, so that only two of the possible six spacer surfaces are in contact with the magnet helium vessels.

The spacer, which takes the compressive load, is made of type 304 stainless steel. A large number of axial holes are drilled in it to reduce its mass without sacrificing load bearing capacity. The spacer is split transversely so that it may be removed from the nitrogen cooled radiation shields surrounding the access ports. This arrangement provides vertical and horizontal holes for access to the experimental volume.

Liquid Nitrogen Cooled Radiation Shields

All surfaces at liquid helium temperature are shielded from the room temperature outer vacuum shell by a liquid nitrogen cooled radiation shield. The shields can be seen in figures 3 and 4. The waffle-type expanded metal shield is made of copper. To minimize its emissivity a ten micron layer of gold is flashed on the shield. The liquid nitrogen flows into the bottom of the shield and up through the waffle-type flow passages as shown in figures 3 and 4, and then into the nitrogen reservoirs. The liquid nitrogen flow is regulated to maintain the liquid levels inside the reservoir. The radiation shields in the spacer bore are liquid nitrogen cooled. But the radiation shields in the magnet bores are conduction cooled by contact with either the spacer bore shields or the end module bore shields. Each module has its own radiation shield, nitrogen reservoir, and nitrogen inlet and vent lines. The radiation shields in the various modules are connected together via tongue-and-groove or lap joints. The radiation shields also serve as thermal shorts for all the connecting pieces between the liquid helium temperature surfaces and the room temperature outer vacuum shell.

Process Instrumentation and Control Systems

Liquid Helium Level Sensing and Control

Liquid helium is sensed at discrete levels within the helium vessels by means of germanium sensors. The resistance of each sensor increases as it is cooled down, and exhibits a step change (due to increased cooling) as its environment changes between cold helium vapor and liquid helium. Approximately 3.6 milliwatts of power per sensor is dissipated in the helium. Conditioning circuitry is used to sense the resistance changes and energize panel lights indicating vapor or liquid for each sensor location.

In addition to the discrete liquid helium level sensors, each helium vessel has a linear liquid helium level sensor consisting of a twelve inch Nb-Ti filament which is powered by a constant current of 70 milliamperes. The portion of the filament in liquid helium becomes superconducting while the rest remains normal, providing a voltage drop proportional to the length of the probe in vapor. These probes are located in the helium vessels to indicate the level in the top twelve inches of the vessel. Signals are taken from these probe circuits and fed into a strip chart recorder to monitor liquid helium boil-off rates. The linear level sensors' indication of liquid level correlates very well with the discrete sensors.

A gallium arsenide diode cryogenic temperature sensor is installed in each of the three windings of each magnet and in each spacer module.

Facility Cooldown and Cryogenic Usage

Cooldown of the facility begins by flowing liquid nitrogen into the radiation shields. Helium gas, cooled to 78° K in a liquid nitrogen heat exchanger, is circulated through the magnet windings via the gas inlet shroud for about 36 hours until the magnets reach approximately 100° K. Then 40° K gas is circulated for about 12 hours until the magnets are cooled to around 60° K. Liquid helium is then introduced at the top of the helium vessel to continue the cooldown to near 4.2° K. A liquid level is established above the magnet windings in about 6 hours from the start of liquid fill.

During the cooldown, the spacers cool by conduction heat transfer at a rate between 1.5 to 2.5° K per hour and reach an equilibrium temperature near 23° K. The contact resistance across the spacer surfaces apparently limits their cooldown rate. Further spacer cooling was not observed until a magnetic field was established. As the interface resistance decreased, due to increased loading between spacers and coils, the spacers started cooling at approximately 3° K per hour reaching a final temperature of about 12° K.

Approximately 3000 liters of liquid helium were used to cool the facility to the point where the superconducting magnets could be energized. This number includes flash and transfer line losses as well as the amount to cool the spacers to 23° K and the magnet coils to 4.2° K.

During steady-state operation, liquid helium consumption varied from 400 to 850 liters per hour. The boil-off rate was measured for each helium vessel. Coil numbers 1 and 3 had a boil-off rate of 68 liters/hr and coil number 2 had 286 liters/hr. The reason for the high use rate in coil number 2 cannot be determined until the facility is disassembled so that such possibilities as heat shorts and helium leaks can be investigated.

Initial Tests

The SUMMA magnets have been powered several times since being installed in the facility. The magnet current charge rates given in Table III were used in these tests and gave quite smooth operation. These rates were established in the magnet acceptance test program prior to their installation in the SUMMA helium vessels.

In all the magnet powerings in the SUMMA facility, the inner windings have been charged to only 25 amps. The current is limited at this time because the windings exhibited some internal shorts between pancakes when the magnets were retested prior to installation in the SUMMA helium vessels. Rather than rebuild these inner windings, it was decided to install them in SUMMA and to power them cautiously. The 25 amp current sufficiently suppresses the flux jumps to preclude the inner windings from causing a normalcy.

Magnet B (figure 1) has been charged separately up to its design currents in the middle and outer windings twice and performed satisfactorily each time. Magnets B and C were powered simultaneously to their design currents in the middle and outer windings and performed satisfactorily.

All three magnets were powered simultaneously to

300 and 420 amps in the middle and outer windings respectively. After satisfactory operation for about ten minutes, the helium vessels began venting helium vapor through their spring-loaded relief valves into the atmosphere. To avoid damage to the windings the magnets were manually discharged through their external resistive shunts at the initiation of the helium venting. The cause of the rapid helium vent appeared to be loss of facility vacuum which would cause rapid heat transfer to the helium vessels. Steps were taken to avoid another loss of vacuum. "0" ring vacuum seal joints, suspected of cold-shocking out, were welded shut. Parts of the vacuum pumping system were moved so that its operation would not be impaired by the strong magnetic fields.

The next time the three magnets were powered simultaneously, they reached about 90 percent of their design currents and the helium vessels again began venting to atmosphere. The facility vacuum held up, and the magnets were again manually dumped through their external resistive shunts to avoid damage to the windings. There were no clear indications of a coil normalcy, but this possibility cannot be ruled out.

Before disassembling the facility to determine the cause of the rapid helium boil-off rate and to correct it, a mirror field will be produced with magnets B and C. Plasma physics tests will be conducted in this magnetic field configuration to test the "Burnout" scaling laws and to test the NASA electrode designs up to central plane magnetic fields of 3.8 T.

The fourth magnet, which is being rebuilt at this time, will be tested and then installed at the time SUMMA is reassembled.

Table III
Magnet Charging Schedule

1. Charge all inner windings to 25 amps.
2. Charge middle and outer windings simultaneously as follows:

Current increment amps	Charge Rates Middle amp/min	Charge Rates Outer amp/min	Time increment minutes
0-100	4	4	25
100-200	2	2	50
200-300	1.33	1.33	75
300-400	-	1.33	75
Total charging time			3 hrs 45 min

Hot Ion Plasma Experiment (HIP)

A "Burnout-type"[5,6,7] steady-state dc plasma heating experiment is planned for SUMMA. A schematic of Burnout experiment is shown in figure 6. Concentric electrodes, located near the mirror throats, produce a hollow cathode discharge. Gas is fed through the center of the cathode. Energy is coupled to the plasma by applying a radially inward electric field between anode and cathode. The mutually perpendicular electric and magnetic fields cause the plasma to rotate (drift) in the azimuthal direction. According to the theory of Hirose and Alexeff[10] an azimuthal current exists because of a drift velocity difference between ions and electrons. This current combined with radial density gradients leads to the growth of electrostatic azimuthal waves at frequencies near the lower hybrid frequency. Hirose and Alexeff postulate that ions are heated in planes perpendicular to the applied magnetic field by the high frequency fields of the wave.

In a preliminary experiment at NASA (HIP-1) the Burnout process was reproduced in a modest magnetic field facility (1.8 T midplane field and 1.6 mirror ratio).[6,7] Parametric changes were made in both electrode geometry and materials to better optimize the production of high ion temperatures. Multiple sources were also operated in HIP-1.

According to the scaling laws developed at ORNL in their "Burnout" experiment, plasma with ion temperatures greater than 10 keV and ion density of 10^{14} cm^{-3} are predicted for the 4.9 T midplane magnetic field strength in SUMMA. The goals of this research are to study problem areas such as plasma wall interactions, reactor fueling techniques, and to obtain the scaling laws required to make a D-T plasma for a large fusion engineering research facility.

Figure 7 is a photograph of the SUMMA facility.

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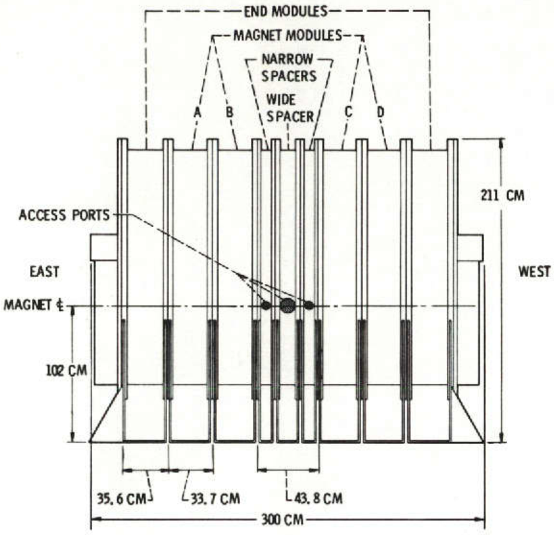

Figure 1. - Side view of SUMMA in simple mirror arrangement.

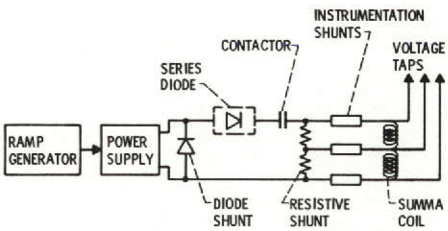

Figure 2. - Magnet power-supply and associated circuitry.

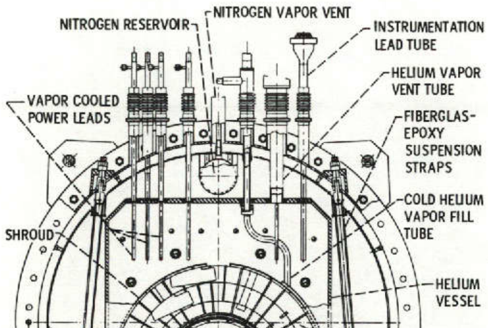

Figure 3. - Cross-section of magnet module.

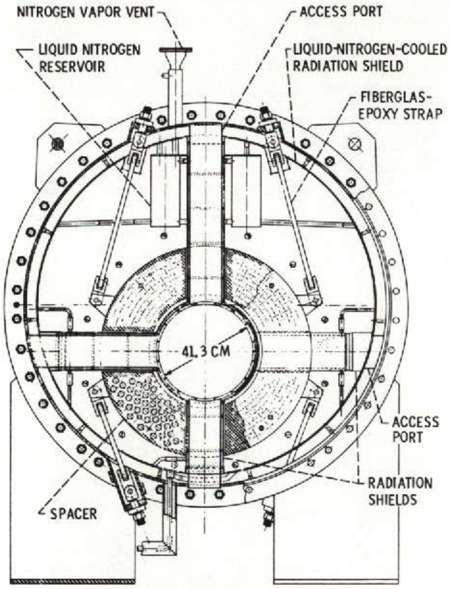

Figure 4. - Cross-section of spacer module.

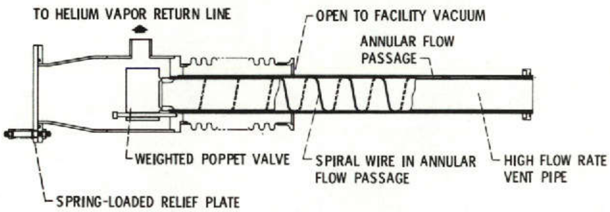

Figure 5. - Vapor-cooled helium vent pipe.

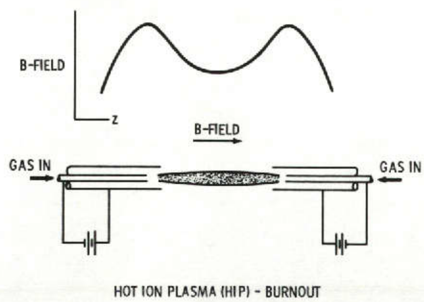

Figure 6. - Schematic of plasma experiment.

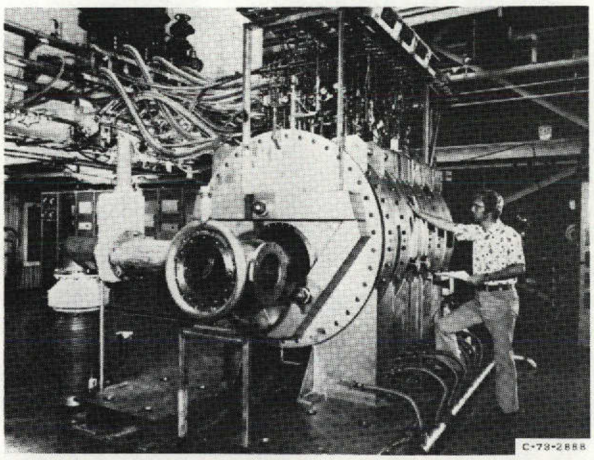

Figure 7. - NASA Lewis Research Center SUMMA facility.

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